FEA Criteria for Thermal-Structural Analysis in Synchrotron Radiation

Presenting authors: Houcheng Huang & Nigel Hammond
Organisation: Diamond Light Source Ltd

Corresponding author: Houcheng Huang
Organisation: Diamond Light Source Ltd
Email: hou-cheng.huang@diamond.ac.uk

Co-author: Jim Kay
Organisation: Diamond Light Source Ltd

Theme: Finite element analysis

Abstract:
In the finite element analysis of synchrotron radiation world, there are a number of specific conditions that have to be considered by engineers. For instance, the gradient of thermal loads from the synchrotron beam is extremely intensive and the Gaussian shape power profile falls on very tiny footprints. Apparently, assumption of an even distribution of power will not predict accurate temperature and deformation. In order to apply such thermal loads more accurately into the FEA model, the footprint is to be divided into a small area grid in a virtual plane perpendicular to beam direction. The size of grid directly affects the results and should be predefined according to power density. In the same time, the FE mesh size is another factor which will affect accuracy of results. We should agree a reasonable fine mesh with our engineers. In heat transfer study, the heat transfer coefficient is also influential. The value of heat transfer coefficient ought to be calculated according to cooling conditions that will assure a structure to be under allowed maximum temperature. Furthermore, the temperature obtained on surfaces of cooling channels should be lower than the boiling point under relevant pressure. In the stress calculation, some material will not behave elastically under certain conditions and therefore elasto-plastic analysis has to be employed, criterion for such procedure must be established too. In this paper, we will discuss some general criteria for finite element analysis in synchrotron radiation field.

1-Problem

Thermal power with photon beam from synchrotron radiation has following categories: 1) from dipole magnets as in Figure 1, the maximum density is of the order of 10^{2} W/mRad^2, 2) from undulators with horizontal or vertical polarisation as in Figure 2, the maximum density is of the order of 10^4 W/mRad^2, 3) from undulator with circular polarisation as in Figure 3, the maximum density is of the order of 10^4 W/mRad^2,

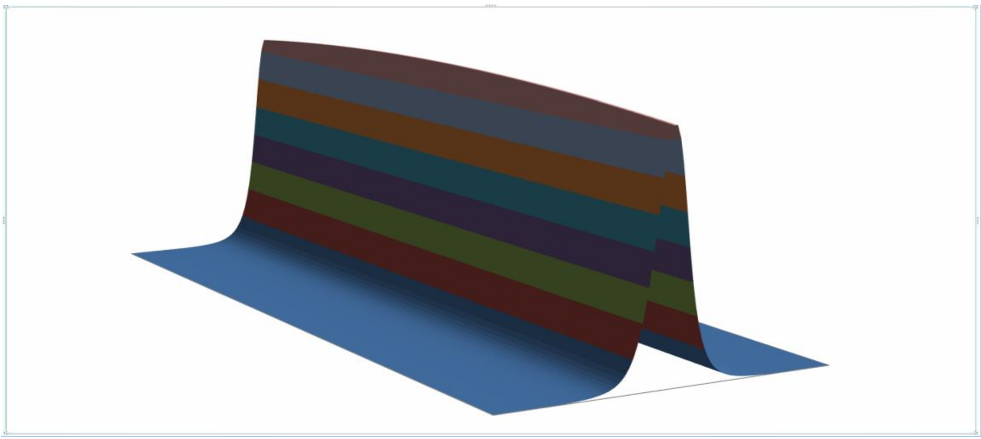

Figure 1. Power density from dipole magnets

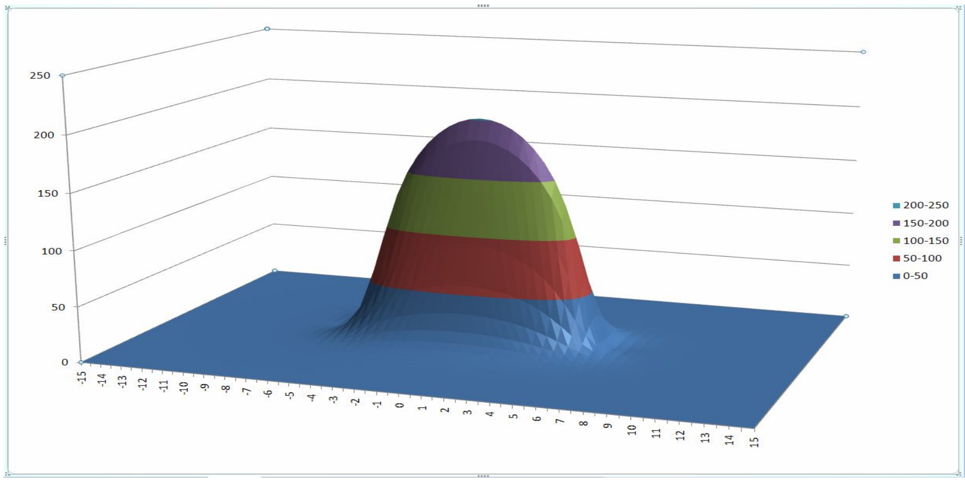

Figure 2. Power density from undulator with horizontal/ vertical polarisation

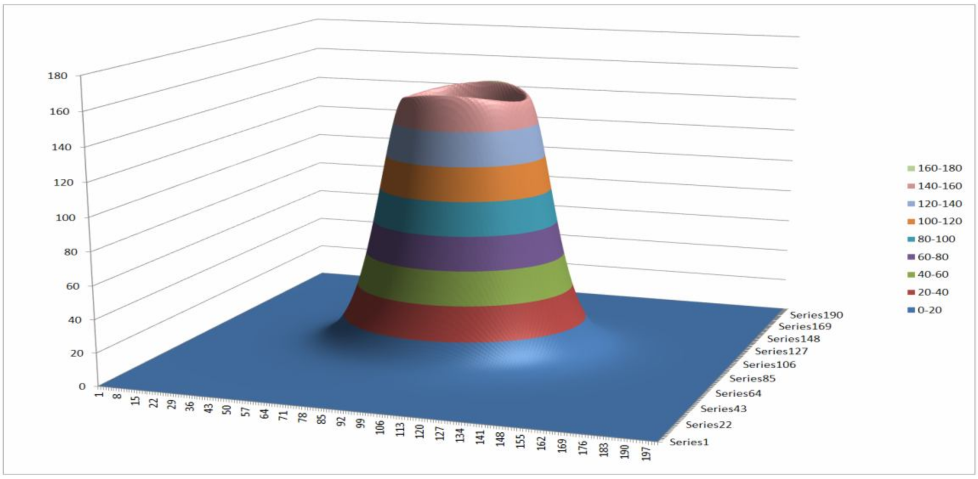

Figure 3. Power density from undulator with circular polarisation

All such beams will fall on a tiny area on the absorbers or on other optical devices. The high density will focus on an area scaled from 1 to10mm depending on the distance from the light sources.

2- Thermal load application.

As mentioned in Section 1, the gradient of thermal loads from synchrotron beam is abrupt and the profile of power is in a Gaussian shape. In order to apply such thermal loads into the FEA model, a grid is created in a virtual plane perpendicular to beam and then the power in each cell projected on to model surfaces as shown in Figure 4. The even power density is assumed and applied to each cell while the total power is kept the same. Reasonable results including temperature and stresses are obtained. However, the accuracy is very much dependent upon cell sizes of such a grid. The FE mesh density is another aspect to be controlled in the following procedure of analysis.

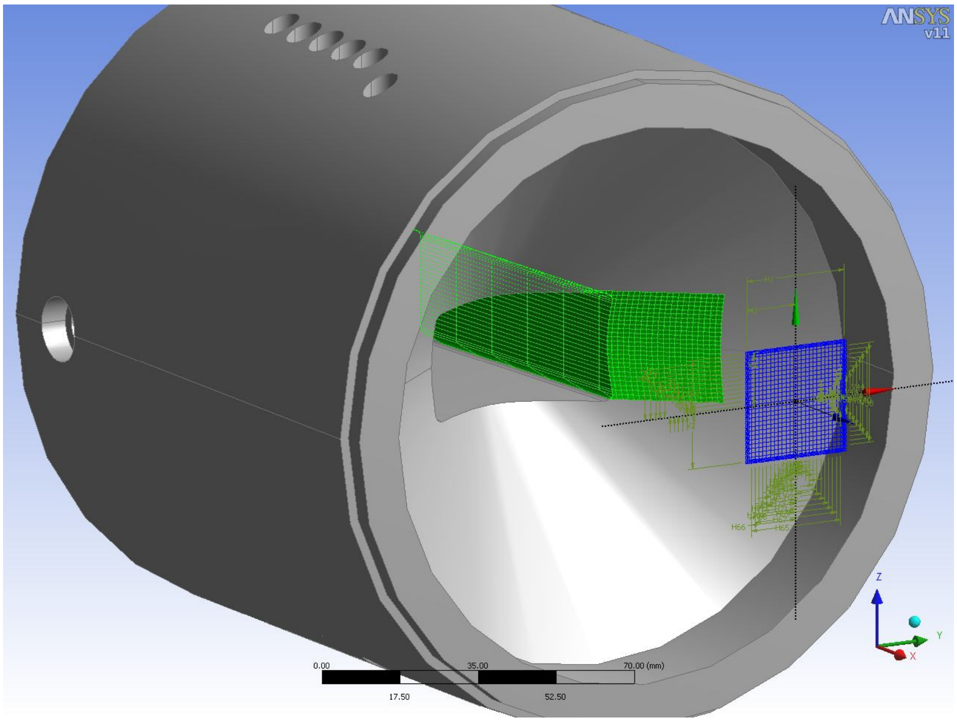

Figure 4. Grid in blue in virtual vertical plane projected onto an aperture

In order to demonstrate the effect of cell sizes of a grid, both elastic and elasto-plastic analyses are performed with different cell sizes for the same beam thermal power with the same FE mesh density. In the Table 1 and 2, it is shown that four different cell sizes (1x1, 2x2, 6x4 and 10x6 mm) were employed in analysing the I09 slit absorber. The highest temperature of 407C^{o} was reached by using 1x1 mm grid while the lowest temperature of 363.2 C^{o} was obtained from a 10x6 mm grid. Similar results were also achieved for stresses and strains.

It is also noted the highest power density is 97% of theoretical value for 1x1mm grid but only 48% for 10x6mm grid.

Table 1: Results for elastic analysis

Elastic analysis for I09 slit absorber

Load Cell size (no. cells) (peak power density%)	h x v (mm)	1x1(420) (97%)	2x2 (120) (84%)	6x4 (25) (65%)	10x6 (9) (48%)
Temperature	(C^)	407.0	399.7	381.9	363.2
Peak strain	(%)	0.154	0.16	0.14	0.14
Stress	(MPa)	166	172	154	149

In the Table 2, the elasto-plastic analysis is conducted to show sensitivity of the elasto-plastic results to the cell sizes. Clearly, the elasto-plastic stresses and strains are much less sensitive to the cell sizes than the temperature is.

Table 2: Results for elasto-plastic analysis

Elasto-plastic analysis for I09 slit absorber

Load Cell size (no. cells) (peak power density%)	h x v (mm)	1x1(420) (97%)	2x2 (120) (84%)	6x4 (25) (65%)	10x6 (9) (48%)
Temperature	(C^)	407.0	399.7	381.9	363.2
Peak plastic strain	(%)	0.11	0.11	0.09	0.09
Bulk plastic strain	(%)	0.075	0.07	0.064	0.06
Stress	(MPa)	38.1	38.1	37.2	36.9

3- Proposed Criteria [1]

1) Cell size for thermal loading

The size of cells for the thermal load application should be defined such that '*the averaged power density in each cell of the vertical virtual plane is equal or greater than 90% of the power density discharged from light sources'*. Cells with the size of 1x1mm for the I09 example produce 97% of real power density. However, the high density of thermal power only focuses in the very small area and therefore adaptive grids can be used as in Figure 6 and 7.

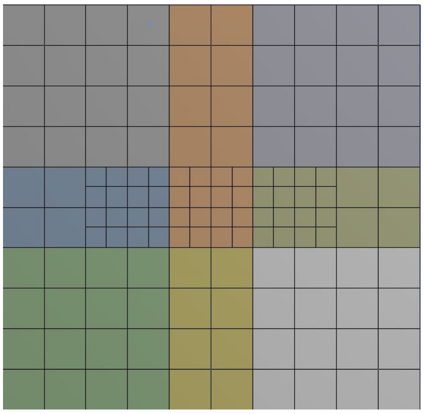

Figure 6. Adaptive grids for H pol.

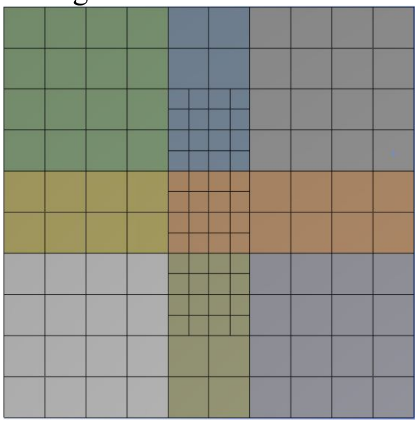

Figure 7. Adaptive grids for V pol

In practice, a very fine grid is created at first, then cells in the area with lower power density can be merged while cells in the area with higher power density are kept unchanged. This method is especially useful for the circular polarisation. However, this criterion is only for ANSYS workbench users. In ANSYS Mechanical (or Classic), adaptive meshes can be generated and then accurate thermal loads can be applied automatically using ANSYS macro files developed by the user themselves [2].

2) Mesh size

At least, "Medium" option in the ANSYS workbench is recommended in our analyses. Two consecutive mesh densities should be used to check convergence. Ideally, adaptive meshes according to estimated temperature/stress gradients are highly advisable.

Table 3: Mesh density effect for elastic and elasto-plastic analysis

	Temp.	E-Stress	E-strain	EP-Stress	EP-strain
Med. mesh:	382	154	0.143%	37	0.13%
Fine mesh:	399	178	0.165%	39	0.16%

3) Heat transfer analysis:

Heat transfer coefficients: $0.01W/mm^2C^o$ to $0.02W/mm^2C^o$ are recommended based on typical conditions of 2.5 to 5.5 m/sec water flow rate under 10 bar pressure with 10mm diameter water channel. Actual applied values should be determined using all mentioned parameters if possible. For water cooling, maximum temperature allowed is 400 C^o. If nucleated boiling of the cooling water is to be avoided then the temperature at surfaces of the cooling channels must be below 165°C, which is the boiling point of water at 6 bar (gauge) pressure (7 bars absolute pressure). 6 bar (gauge) is the lowest water pressure recorded in the front ends.

Table 4: Effect of Heat transfer coefficient to FEA results

Effect of heat transfer coefficient

Elastic analysis for I09 slit absorber (1x1mm cell)

Heat transfer coefficient: h	(W/mm^2C)	0.01	0.015	0.02
Temperature	(C^)	407	329	286
Peak strain	(%)	0.15	0.14	0.13
Stress	(MPa)	166	149	137

4) Stress analysis for OFHC

All analyses for OFHC structures initially carried out were linear elastic. The rule for acceptance of stresses resulting from elastic analyses is that if the (Von Mises) stresses are less than 250MPa then there is no need to perform a non-linear elasto-plastic analysis. These linear stresses are fictional, as the material will have yielded in reality and these high stress levels could not be achieved, but it serves as a useful yardstick (or indicator) to assess whether further analysis is necessary. However, if peak stress is over 250MPa then elasto-plastic analysis has to be conducted to take strain into account as criteria for the design limit that is 0.5% peak strain and 0.1% in the bulk body [3].

4- Conclusions

As mentioned above, to maintain consistency for FEA analysis for DLS engineering, we have internal criteria shown in the Table 5.

Table 5 FEA criteria for thermal-structure analysis

Power cell size (% of density)	Mesh density	Heat transfer coefficient – Water- (W/mm^2 C)	OFHC structure				
			Body temp (C)	Cooling channel temp (C)	Elastic stress (MPa)	Elasto-plastic bulk strain (%)	Elasto-plastic peak strain (%)
=>90	medium	0.01-0.02	>=400	<=165	250	0.1	0.5

References

[1] H. Huang, Technical note for some criteria in Finite element analysis. Internal research report of Diamond Light Source Ltd

[2] H. Huang and J. Kay, Vibration and Thermal dynamic analysis in synchrotron radiation. The proceding of NAFEMS World Congress pp. 122, May 22^{nd}-25^{th} 2007 Vancourver, Canada

[3] H. Huang, Thermal analysis of dipole crotch absorber. Internal research report of Diamond Light Source Ltd